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# Optional Stopping and the Termination of Memory Retrieval

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## Abstract
Recent years have seen an increased interest in understanding memory-retrieval dynamics and, in particular, what makes a person decide to terminate the memory-search process. We review research that has employed the open-ended retrieval paradigm (Dougherty & Harbison, 2007) and focus on the behavioral regularities it has revealed. The main finding of this research is that people's memory-search behavior follows a lawful pattern of a convex decreasing relation between exit latency, or the time between the final retrieval and the decision to terminate search, and the number of items retrieved. Theoretical work has converged on a stopping rule that treats the retrieval process as a costly cognitive process that is truncated on the basis of a comparative judgment of perceived relative benefit. Parallels with other search domains are highlighted.

## Keywords
free recall, search termination, cognitive search, stopping rules

What are the names of your fourth-grade classmates? To answer this question, you might recollect various features of your old elementary school, or familiar faces or images from your time in school, and you may even bring to mind all those fond memories of running around the playground. The memories of some of your childhood friends will no doubt come bubbling to mind—but like everything else in life, your delightful trip down memory lane will eventually come to an end, and you will be pulled back to the here and now to finish another drab article on memory retrieval. There is no preset limit on how long you can peruse your memory: There is no external clock dictating when it is time to get back to work or to move on. The decision to terminate memory search is entirely voluntary and under your control. But what processes govern your decision? Why do some people persist in recall longer than others? And how do decisions to terminate memory search affect the outcome of the retrieval process?

The impetus for investigating memory-search-termination decisions is given by the fact that a great majority of real-world tasks that involve memory retrieval end with these decisions. Scientifically, there is a need to accurately characterize the processes involved in memory retrieval so that mechanisms included in the theories and computational models of memory are justified empirically. From a more pragmatic perspective, there are many domains in which termination decisions may influence other cognitive processes that use information retrieved from memory. For example, physicians are known to generate diagnostic hypotheses from memory when diagnosing patients. How do they decide when to terminate the generation process, and do these termination decisions affect their diagnostic accuracy?

## A Paradigm for Measuring Memory-Search Termination

It is clear that just as every act of retrieval must be initiated, it must also be terminated. The question is, how do people decide to terminate retrieval? In laboratory experiments on memory, the predominant approach has been to impose a limit on how much time the participant has

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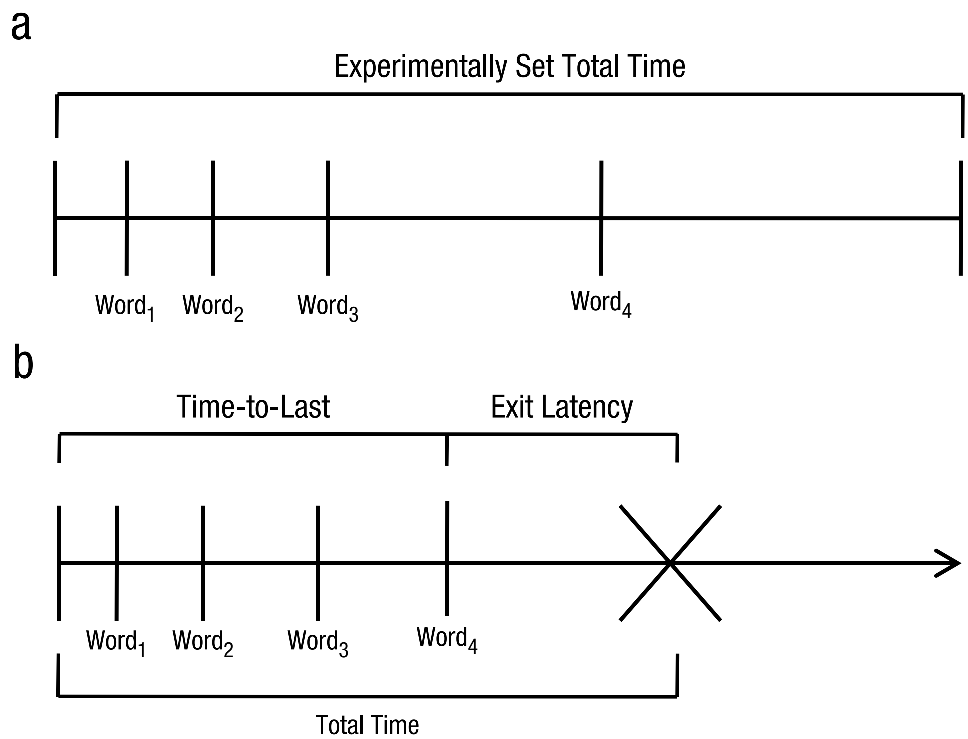


**Fig. 1.** Depiction of the standard experimenter-ended retrieval paradigm (a) and the open-ended retrieval paradigm (b). Note that in the open-ended paradigm, the retrieval interval is terminated by the participant (indicated by the "X") and varies from retrieval list to retrieval list, as well as between participants. This is in contrast to the standard paradigm in which the total time spent in search is always the same.

to retrieve. In a typical experiment, participants are presented with a series of to-be-remembered items and then asked later to retrieve as many items from the series as possible. To exert some control over the task, the experimenter typically determines just how much time the participant has to retrieve, with intervals across experiments often set to 30, 45, 60, or 90 seconds (see Miller, Weidemann, & Kahana, 2012), depending on the length of the studied list, to allow enough time for the participant to retrieve the items. This method is illustrated in Figure 1a, which depicts a hypothetical free-recall task. Note that within this paradigm, the experimenter, not the participant, determines when memory search will be terminated. Further, with this method, it is unclear how long participants persist in memory search: Do they continue to actively search memory for the duration of the entire interval, or do they self-terminate prior to the response deadline?

Dougherty and Harbison (2007) proposed a simple modification to the standard memory-retrieval paradigm. Rather than having the amount of time allotted for retrieval determined for them by the researchers, participants made these decisions. This method, which we refer to as the *open-ended retrieval paradigm*, is depicted in Figure 1b. In contrast to the standard closed-interval paradigm, in the open-ended paradigm, participants simply inform the experimenter when they are finished retrieving a particular list, either by pressing a designated key on a keyboard or by verbally indicating that they are finished. This simple modification indexes precisely when in the retrieval process participants have decided to terminate the active, or controlled, search of memory. Moreover, the paradigm introduces three additional latency measures, which are important for determining what factors influence termination decisions: total time, time-to-last, and exit latency. *Time-to-last* is the latency between the initiation of the retrieval episode and the time at which the final item is retrieved. *Exit latency* is the time between the final retrieval and the participant's decision to terminate search. *Total time* is the sum total of the time-to-last and the exit latency.

## Behavioral Regularities

Studies using the open-ended retrieval paradigm (Davelaar, Yu, Harbison, Hussey, & Dougherty, 2013; Dougherty & Harbison, 2007; Harbison, Dougherty, Davelaar, & Fayyad, 2009; Hussey, Dougherty, Harbison, & Davelaar, 2014; Unsworth, Brewer, & Spillers, 2011) have shown a remarkably consistent pattern, which is

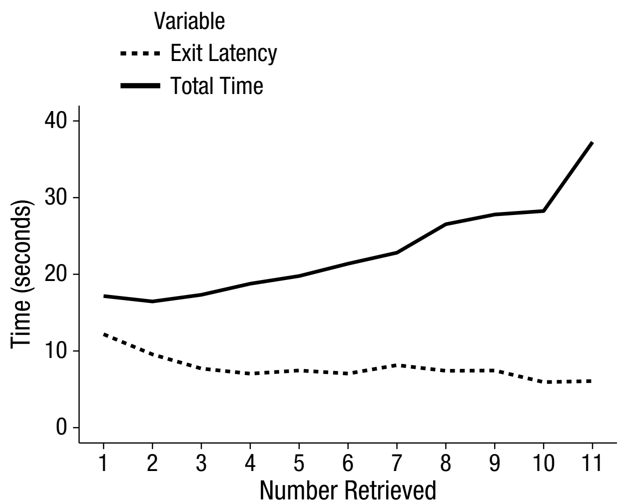


**Fig. 2.** The average total time and exit latency across three experiments using the open-ended retrieval paradigm (Dougherty & Harbison, 2007; Harbison, Dougherty, Davelaar, & Fayyad, 2009).

depicted in Figure 2. The more items that are retrieved from memory, the longer the time-to-last and the total time spent in search. In contrast, exit latency *decreases* with the number of items retrieved.

Termination decisions also appear to impact another temporal variable of memory retrieval, the inter-retrieval time (IRT). IRTs are the times between successive retrievals (i.e., the time between the first and the second retrieval, the second and the third retrieval, etc.). Research using the standard closed retrieval design in which the experimenter determines when memory search should be terminated has consistently found dramatic growth between IRTs, such that the final IRT—the IRT between the penultimate and the final retrieval—is much greater than the immediately preceding IRT (Murdock & Okada, 1970). This result has been important for informing models of the memory-search process (see Davelaar, 2008). However, when an open retrieval design is used, the increase in IRTs is much less dramatic. Specifically, the final IRT is significantly smaller when participants are allowed to terminate their own memory search (Hussey et al., 2014). Despite this decrease in the final IRT, we found no significant change in the number of items retrieved—in other words, participants were able to retrieve as many items as participants in a closed retrieval design, but in less total time, which suggests that memory retrieval may be more efficient than indicated using the standard experimental design. A possible explanation for this result is that people rely on the external allocations of time when such allocations are salient (e.g., in experiments using the closed interval paradigm) and ignore the internal signals that underlie self-terminated search.

## Proposed Rules for Search Termination

The construct of a stopping rule is not new to cognitive psychology. Simulation models of memory have long included rules for terminating search. However, the majority, if not all, of the proposed stopping rules have lacked empirical grounding. Harbison et al. (2009) identified four rules that were proposed in past research:

1. *Total time:* Terminate retrieval when a preset amount of time has elapsed (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005).
2. *Successive failures:* Terminate retrieval after some number of consecutive retrieval failures (Metcalfe & Murdock, 1981; Thomas, Dougherty, Sprenger, & Harbison, 2008).
3. *Rate decrease:* Terminate retrieval when the rate of retrieval decreases below some threshold (Young, 2004).
4. *Total failures:* Terminate retrieval after some number of total retrieval failures (Raaijmakers & Shiffrin, 1981).

These four rules produce distinct signatures in terms of the total time, time-to-last, and exit latencies, as indicated in Figure 3. Note that for the total-time rule, exit latencies decrease as a function of the number of items retrieved and total time stays constant, whereas the successive-failures and rate-decrease rules produce the exact opposite pattern of results. The total-failure rule, however, predicts that exit latency decreases and total time increases with the number of items retrieved, and is consistent with the data shown in Figure 2.

## What Factors Compel People to Persist in or Truncate Search?

Although there has not been much research on sources of variability in memory-search-termination decisions, a few studies offer promising leads. Dougherty and Harbison (2007) and Harbison et al. (2009) showed that individual differences in exit latencies were correlated with scores on the Decisiveness subscale of the Need for Closure scale (Webster & Kruglanski, 1994). The Decisiveness scale includes items such as "When faced with a problem, I usually see the one best solution quickly," and arguably measures one's propensity to make quick decisions. More decisive people tend to have shorter exit latencies; they spend less time continuing memory search after the final successful retrieval and yet retrieve the same number of items. This could lead them to terminate search prematurely, an aspect that has not yet been investigated. Other variables that may be relevant to search-termination decisions include impulsiveness and risk taking, though it

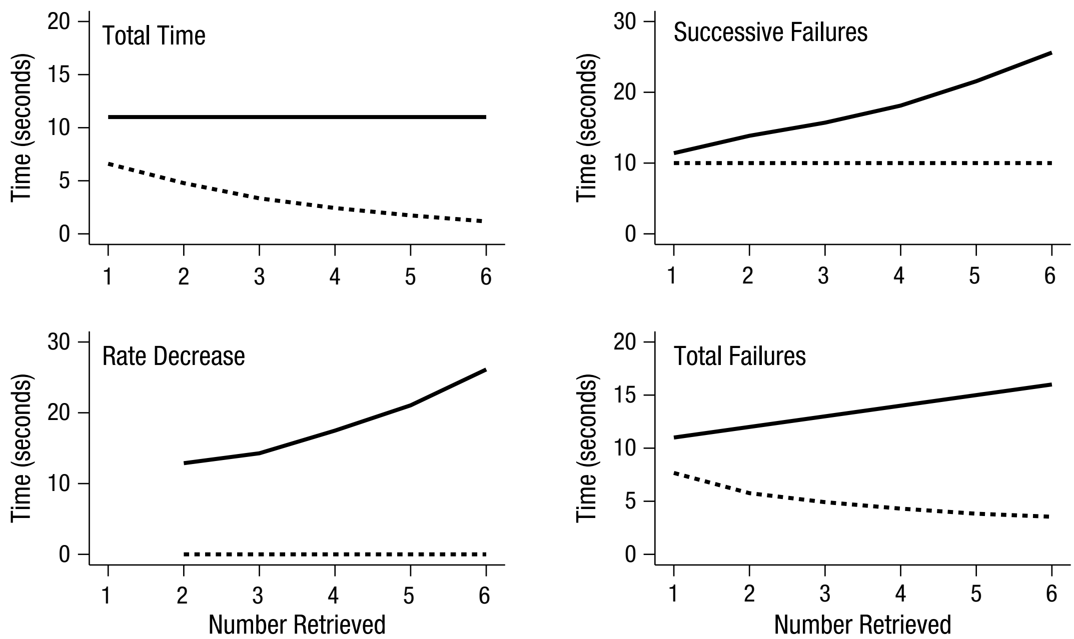


**Fig. 3.** Predicted total time and exit latency based on four different stopping rules. This simulation used a sampling-with-replacement model in which the relative probability of sampling each of the seven list items was equal (1) and the probability of recovering each sampled item was .63. The total-time and exit-latency predictions of the stopping rules are robust over variations in relative sampling and recovery probabilities.

appears that termination decisions are unrelated to individual differences in working memory (Dougherty & Harbison, 2007).

In a separate study, Davelaar et al. (2013) found that termination decisions were sensitive to variations in payoffs for retrieving items. As shown in Figure 4a, when the payoffs were favorable (i.e., +150 points per correct retrieval and −50 points for every second spent on search), participants had longer exit latencies and spent longer searching memory than when payoffs were unfavorable (i.e., +50 points per correct retrieval and −150 points for every second spent on search). This pattern is consistent with the total-failures rule (see Fig. 4b), but the threshold for terminating search was lower in the unfavorable than in the favorable condition.

Unsworth et al. (2011) examined people's confidence in their retrievals—that is, whether they judged the item they retrieved to be in the memory set. In three experiments, the researchers asked participants to indicate their confidence in their just-typed response in an open-ended recall task. Exit latencies were shorter if the final retrieved item was associated with low confidence, suggesting that confidence influences search-termination decisions.

A key property of many free-recall experiments is the presence of intrusion errors. Intrusions are items retrieved from memory that were not part of the study list. Miller et al. (2012; see also Laming, 2009) suggested that memory-search-termination decisions are triggered by intrusion errors and showed that search termination is correlated with intrusion errors. However, because confidence generally decreases as a function of number of items retrieved (Unsworth et al., 2011), allowing more intrusions, and because termination decisions always occur after a number of retrievals, search termination following intrusions may be epiphenomenal (for an analysis, see Harbison, Davelaar, Yu, Hussey, & Dougherty, 2013). More work is needed to determine if intrusions are causally related to search-termination decisions.

## Stopping Decisions in Other Domains

Stopping decisions have been investigated in other domains as well, including convergent decision-making tasks (Townsend & Wenger, 2004), problem solving (Payne & Duggan, 2011), and information-search tasks (Pirolli & Card, 1999). Information search, in particular, draws heavily from work in the animal-foraging literature.

It is interesting to note that the total-failures rule is similar to the incremental-stopping rule, which describes when animals terminate foraging in one food patch in order to move to another and has been found to be most effective when animals are foraging for patchily distributed resources (for discussion, see Wilke, Hutchinson, Todd, & Czienskowski, 2009). This rule also captures

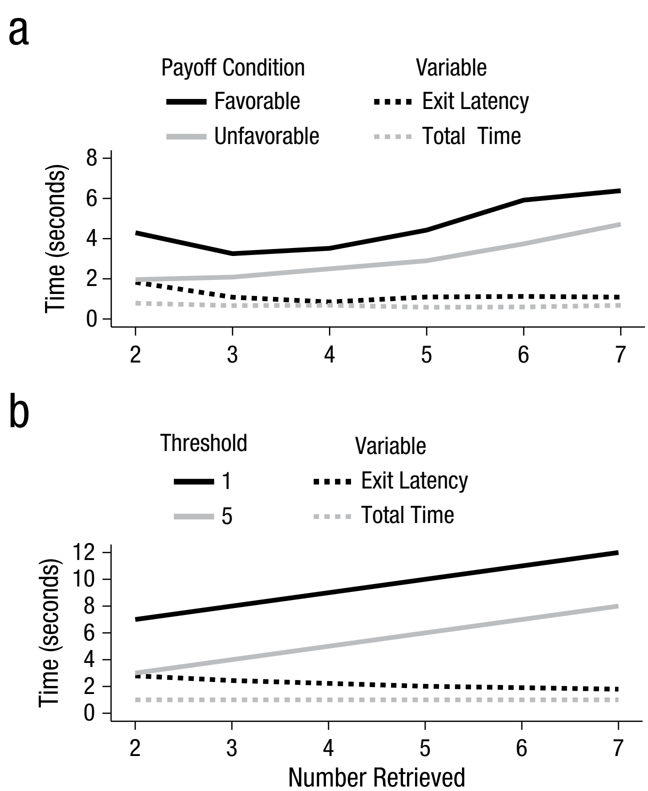


**Fig. 4.** Mean total time and exit latency for participants in the favorable and unfavorable payoff conditions in Davelaar, Yu, Harbison, Hussey, and Dougherty (2013; a) and predictions of the total-failures rule for two stopping thresholds (b). Note that our simulation used the same model and same relative probability of sampling and recovery as those used for Figure 3; the only change was in the stopping threshold. We assumed that participants would adopt a lower threshold for stopping under conditions in which expected costs exceeded payoffs (i.e., in the unfavorable condition). The stopping threshold was set to 5 failures for the favorable condition and 1 failure for the unfavorable condition, in contrast to the threshold of 10 failures used for the total-failure rule in the simulations reported in Figure 3.

how people perform in free recall from semantic memory (Hills, Jones, & Todd, 2012; but see Abbott, Austerweil, & Griffiths, 2012) and terminate external visual search for uniformly distributed targets (Wolfe, 2013), but deviations have been observed when there is large variability in patch quality (Cain, Vul, Clark, & Mitroff, 2011; Wolfe, 2013). In addition, the total-failures rule can be viewed as a special case of a rational model that explicitly accounts for gains associated with successful retrieval and costs associated with time spent retrieving, but in situations in which gains and losses are symmetrical (Davelaar et al., 2013). The important similarity is that every newly retrieved item is subjectively less rewarding, and therefore marginal utility decreases as a function of the number of items retrieved. The relationship between the total-failures rule and utility maximization provides a substantive foundation for the total-failures rule that hitherto has not been recognized in the literature.

These connections to other cognitive domains and literatures are suggestive of a common underlying mechanism. Hills (2006) argued that area-restricted search, which is essentially identical to a retrieval-failures model, is found across animal species (and thus is evolutionarily old) and is likely to be relevant to a wider range of cognitive domains (see Todd, Hills, & Robbins, 2012). An open question is whether the mechanisms governing termination decisions at the level of total retrieval time relate to decisions to terminate search within one category and switch to the next. Such a demonstration would further support the generality of the underlying mechanisms and the utility of the open-ended retrieval paradigm in particular.

## Conclusions

Memory-search-termination decisions are remarkably consistent and have been best described as following a total-failure stopping rule, with each failure to retrieve increasing the chance of the decision to terminate search. By including this decision in experiments on memory retrieval, the results can be more cleanly applied to understanding search in many real-world settings, such as diagnostic hypothesis generation. Its inclusion also informs our understanding of how people search their memory—for example, how long they are willing to continue before giving up, how this factor is influenced by motivation, and how it can be influenced by characteristics of the retrieval task, such as payoffs. The open-ended paradigm can be applied outside the domain of memory to explore termination decisions in tasks such as visual search and problem solving and is informative for the development of models of higher-order cognition (Thomas, Dougherty, & Buttaccio, 2014; Thomas et al., 2008).

### Recommended Reading

Harbison, J. I., Dougherty, M. R., Davelaar, E. J., & Fayyad, B. (2009). (See References). An overview of various alternative stopping rules for memory search.

Hills, T. T., Jones, M. N., & Todd, P. M. (2012). (See References). A broad theoretical treatment of the role of stopping rules.

Miller, J. F., Weidemann, C. T., & Kahana, M. J. (2012). (See References). An evaluation of relationship between intrusion errors and search termination.

### Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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